3 Soil fertility

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3.1 Introduction

In *Soil Conditions and Plant Growth*, 9th Edition, E.W. Russell (1961) stated that 'a soil can only be fertile if it is a favourable environment for root growth' and that 'the root system … must also take up enough water and nutrients for the crop to give a good yield of whatever part is required'. The concept of 'soil fertility' is one way that soil scientists immediately engage the interest of gardeners and farmers; both hope that the scientists will answer one of their key questions: 'How can I manage this land in order to obtain the best and most profitable yield from it year after year?' All would agree that soil fertility has something to do with the capacity of a soil to support plant growth.

Soil fertility is a deceptively familiar term, but nonetheless an elusive one, where the disciplinary use of the term and its everyday use often do not agree (Patzel *et al*., 2000). To what extent is soil fertility a fixed characteristic of the site itself and to what extent is it the result of management and hence under the control of land managers? Which properties of soil (and of the plants themselves) should be measured to give a robust assessment of soil fertility? If crop yields are maintained or increasing, then can we simultaneously speak of a decline in soil fertility? As different approaches are taken in answer to these and similar questions, it has been possible to identify only an 'observable mess of implicit, indirect and either over-stretched or over-restricted definitions of soil fertility' (Patzel *et al*., 2000).

In the UK, the Agricultural Advisory Council (1970) recognised the range of definitions in use amongst agricultural scientists, advisors and farmers and hence adopted a broad definition to underpin a review of practice: 'we have regarded the qualities which make up a soil's fertility as those which allow crops to grow and produce optimum yields'. In this chapter, we will take this broad definition as our foundation and then briefly consider some of the frameworks within which soil fertility has been considered, highlighting the soil–plant interactions which lie at the heart of a full and integrated understanding of soil fertility. Finally, we will consider how advice on the management of soil fertility has developed and outline the challenges which remain for practical management of soil fertility in the future.

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3.2 Concepts of soil fertility

3.2.1 Links between soil fertility and land capability and suitability assessment

Land use patterns and their spatial distributions at a global scale are driven largely by climate, giving broad agro-ecological zones. At regional/local scales, geology, in combination with climatic patterns, has a critical role together with associated variation in topography (gradient, aspect), hydrology, soil depth and erosion risk (FAO, 1996). To support effective and sustainable crop production, it is important to understand any permanent constraints to land use and crop yield which cannot be (economically) overcome by management and within which any farming system must be adapted. Land evaluation using a land capability classification approach was developed for farm planning in the USA by Klingebiel and Montgomery (1961) and has since been adapted and widely used across the globe. Permanent constraints (which may vary in importance in different climates/regions) are defined as limiting factors and used to assess land use capability. With this approach, it is the negative/limiting features of land which are taken into account to assign a land capability class, with the exception of location and accessibility. Few soil characteristics are routinely considered for land capability classification. The factors that are measured are those which lie beyond the control of the farmer: extremes of soil texture, soil depth and stoniness. Soil texture (the relative amounts of differently sized mineral fractions: sand silt and clay) and stoniness are inherent properties of the soil strongly related to characteristics of the parent material and cannot usually be easily or quickly changed. These inherent properties largely define the ranges within which management is able to control a number of soil properties, e.g. the formation and stability of soil structure, soil consistence/workability during tillage, infiltration capacity and depth and penetration of water and the capacity of soil to supply and retain nutrients. So, e.g., it is possible to give some general information on a range of soil characteristics based simply on the knowledge of its texture: a silty loam will tend to slake and cap at the surface; a sandy loam will hold less water and tend to become acid more quickly and its capacity to hold nutrients will be relatively low. However, even where all the permanent limiting factors are understood, land cannot be simply graded from best to worst on a single scale without taking its use into consideration (Gibbon, 1961).

The development of a Framework for Land Evaluation (FAO, 1976) was deliberately focussed on the assessment of land suitability in relation to particular defined land uses, i.e. 'Fitness for Purpose'. In these assessments, consideration of both permanent (inherent) and manageable constraints is included. As most suitability assessments have been carried out for various types of crop production, the factors used to define subclasses are commonly those associated with definitions of soil fertility (e.g. droughtiness, soil nutrient deficiencies, waterlogging, ease of cultivation). Definitions of suitability classes are expressed in terms of expected yields and/or the level of inputs required to achieve good yields. Measuring potential productivity along a continuous scale, rather than in discrete classes, is also possible through the use of arithmetic formulae combining key limiting factors within a number of parametric approaches to land/soil appraisal, e.g. Riquier *et al.* (1970) and Beatty *et al.* (1979).

Common to all these approaches is the identification of constraints to crop production (Figure 3.1) and the development of inputs and/or management practices which overcome these constraints, so that crop yield potential defined by genetic and climatic factors can be

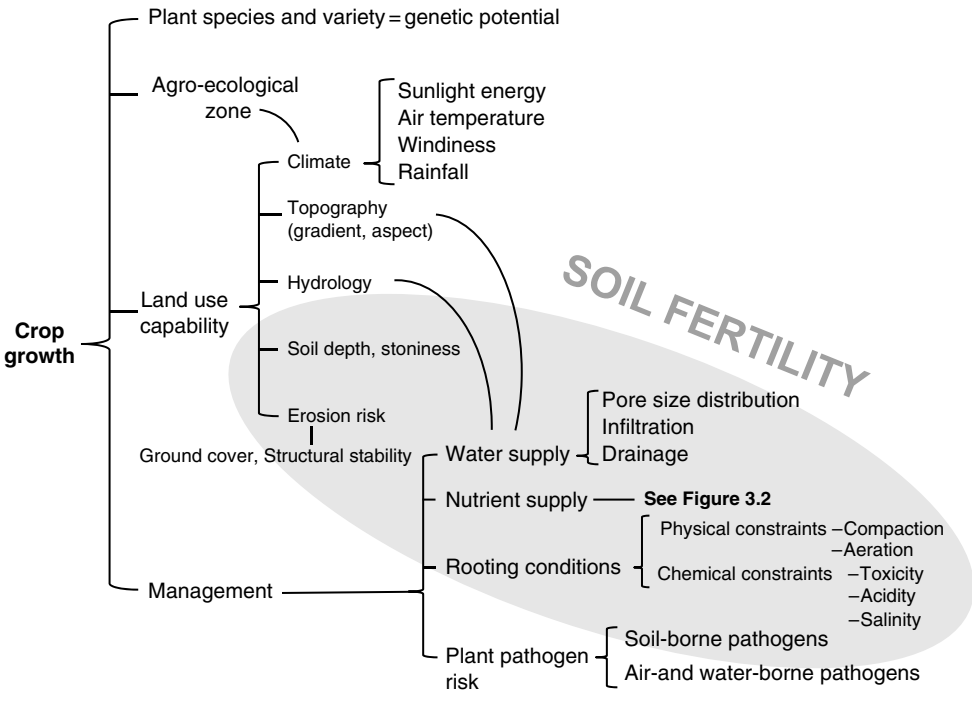


Figure 3.1 Potential constraints to crop growth include plant, climate and soil factors and their interactions. Soil fertility is defined by those soil factors which constrain crop growth. The key limiting factors in any location will vary, e.g. some locations are prone to salinity which then provides the major growth limiting factor, while other regions are mainly limited by acidity, drought, nutrient supply, etc. Liebig's law of the minimum suggests that crop growth will be constrained by the most limiting factor and that changes in other factors will have little impact on growth until they become most limiting. Where several constraints are high, but no single constraint is extreme, improvement of conditions in relation to either constraint will increase yield. Interactions also occur between the impacts of constraints on yield; e.g., with increasing salinity, drought stress is seen at higher levels of water availability. Crop variety selection can also be used to overcome some constraints as a result of the development of varieties with increased tolerance, e.g. aluminium toxicity, salinity.

achieved. Russell (1937) identified the main soil constraints to crop growth that can be controlled through management as water supply, nutrient supply, soil reaction (including acidity, salinity), erosion risk and depth of soil. Factors defining many of these constraints are routinely included in suitability assessments.

3.2.2 Equating soil fertility with the soil nutrient reserve

As described in Chapter 1, the role of the soil in supplying plant nutrients was at the heart of early controversy in agricultural science; developing, then patenting artificial manures provided much of the income stream for early research. As a result, the availability and use of fertilisers has expanded greatly on a global scale (see Section 1.5.4). Consequently during the twentieth century, soil fertility research often focussed on 'the study of all factors which affect the nutrition of agricultural crops' and 'how growth conditions for plants can be improved by manuring or fertilising' (de V Malherbe, 1964). This is not a small area of focus (Figure 3.2). Consequently for many agricultural scientists, the term 'soil fertility' developed a relatively

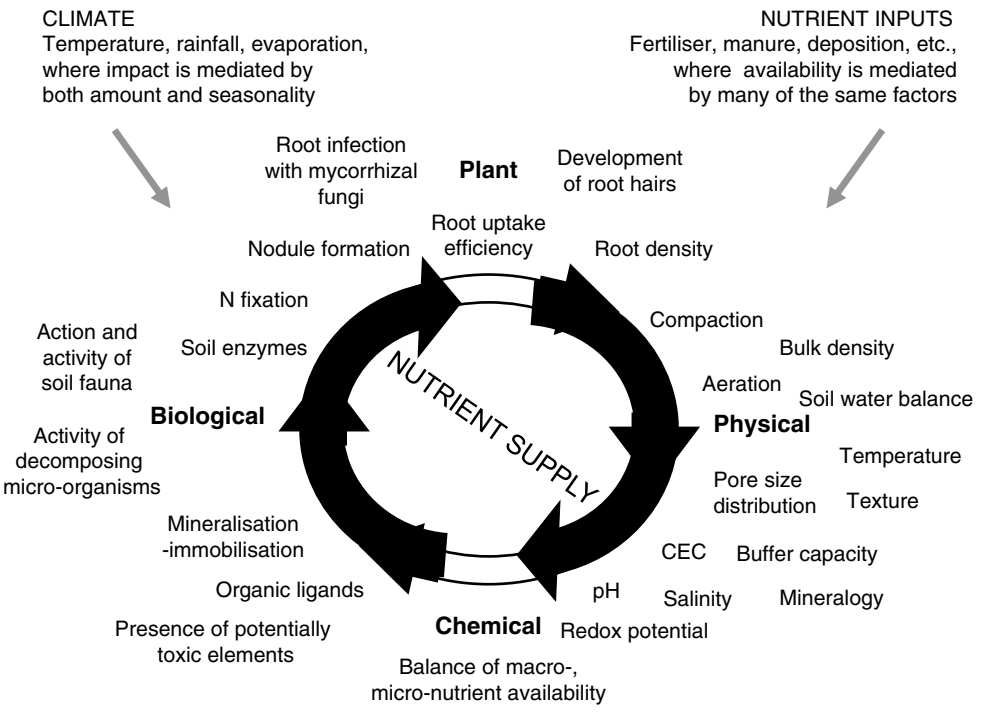


Figure 3.2 The interaction of plant/root, chemical, physical and biological factors in the soil with management (nutrient additions) and climate control nutrient supply to plants; presented as an example of how the main constraints to crop growth (Figure 3.1) can be considered to result from plant–soil interactions. Complex interlocking processes in the soil determine the amounts of essential plant nutrients present, their availability to crop plants, the transformations they undergo in soil, loss mechanisms, processes making them unavailable or less available to crop plants and the most appropriate means of replenishing them. Many agricultural and soil science textbooks in the twentieth century, most of them with the term 'soil fertility' in their title, have focussed solely on these issues and their practical management.

narrow meaning restricted to consideration of a soil's potential to supply nutrients for crop growth. This does not mean that the impact of other factors on yield, such as water availability or poor structure restricting root growth, were considered less important, but simply that these were considered separately to the management of soil fertility by fertiliser addition.

3.2.3 Understanding soil fertility in relation to concepts of 'soil quality'

At the end of the twentieth century, the concept of soil quality developed alongside an increasing awareness and valuation of the goods and services provided by ecosystems globally to support human life (Costanza *et al*., 1997; Millenium Ecosystem Assessment, 2003) and the central role of the soil in the delivery of a range of key functions (Lal, 2001). Soil quality as defined by the Soil Science Society of America (Doran and Parkin, 1994) is 'the capacity of the soil, within land use and ecosystem boundaries to sustain biological productivity, maintain environmental quality and promote plant and animal health'. But the standard against which soil quality is to be compared is rarely agreed or well defined and, as the definition by Doran and Parkin indicates, it must be assessed in relation to the intended use of the soil: 'Fitness

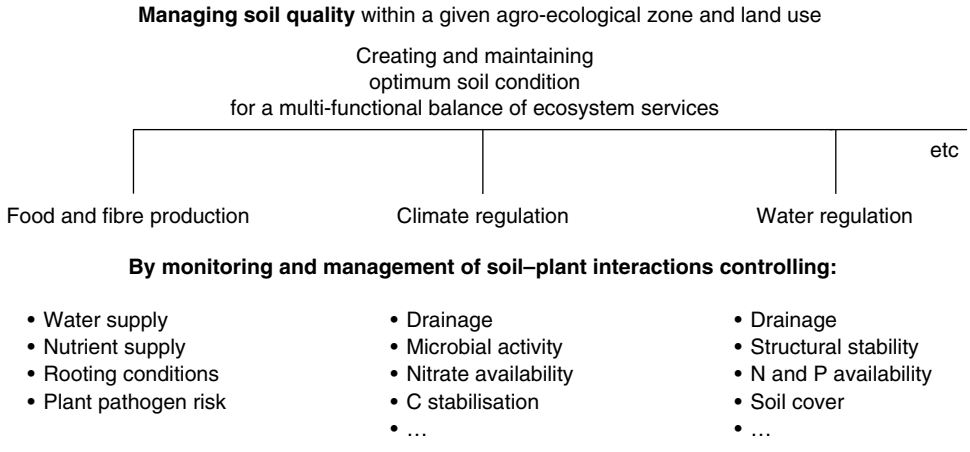


Figure 3.3 Maintaining optimum soil condition for food and fibre production (soil fertility) is one aspect of the management of soil quality. Soil quality frameworks need to take account of the requirement for soils to deliver a range of ecosystem services including provisioning (e.g. food, fibre, freshwater, genetic resources), regulating (e.g. climate, disease and water regulation), cultural (e.g. recreation, educational, cultural heritage) and supporting services (e.g. soil formation, nutrient cycling and primary production). The key ecosystem services required at any site and consequently the underpinning soil functions/characteristics required will vary according to location and societal demands.

for Purpose' again. The utility of an overarching concept of soil quality has been debated (Karlen *et al*., 2001; Sojka *et al*., 2003) but it now stands alongside definitions of acceptable measures of air and water quality in guiding environmental public policies. These issues are considered in more depth in Chapter 12.

It is clear, however, that embedded within all definitions of soil quality there is a recognition of the role of the soil in supporting food and fibre production, i.e. soil fertility as broadly defined (Figure 3.3). The relative emphasis given to aspects of soil fertility in the assessment of soil quality at any site will depend on the intended land use and the location; e.g., if the site is within a key catchment determining water supply for a city or next to a protected wildlife habitat, the role of the soil in supporting food and fibre production would not be a key priority. Many of the early examples of soil quality assessment cited in the literature focussed on crop productivity as they were carried out in agricultural areas (e.g. Romig *et al*., 1995; Sinclair *et al*., 1996; Stenberg, 1999) and are similar to the integrating approaches used for crop suitability assessments (see Section 3.2.1). Food and fibre production is recognised as a key soil function in all current definitions of soil quality. In this context, soil fertility might be regarded as the state of soil required for the effective performance of this function. Although some authors appear to use the terms interchangeably, soil fertility is not synonymous with soil quality and it should be considered as one aspect of a more integrated definition of soil quality.

3.2.4 Defining soil fertility in relation to ecosystems dynamics

The large diversity of soil organisms and their interactions (predator–prey and extensive omnivory) are the driving force behind many soil functions, including nitrogen (N) and phosphorus (P) mineralisation, structure formation and stabilisation, and consequently underpin

Table 3.1 Annual average biomass (kg C ha^{-1}) and simulated contribution to overall N mineralisation (kg N ha^{-1}) for the 0–10 cm layer of a winter wheat field under integrated management for key groups of soil organisms.

Soil organism group – by functional group if considered in the model	Average biomass (kg C ha^{-1})	Modelled annual N mineralisation (kg N ha^{-1})	% Reduction in amount of N mineralised if fauna group removed from the model
Bacteria	373.1	52.96	–
Fungi	21.0	4.53	–
Protozoa			
Amoebae	6.09	13.63	32.4
Flagellates	0.35	0.82	1.9
Nematodes			
Bactivorous nematodes	0.41	6.03	17.3
Fungivorous nematodes	0.02	0.05	1.2
Predatory nematodes	0.25	1.62	19.1
Enchytraeids	0.19	0.45	3.2
Earthworms	8.86	0.47	Not simulated

Data for small pools of soil microarthropods are not presented. The importance of predation in driving overall N mineralisation is shown by the relative increase in the estimated contribution made to mineralisation when it is estimated by the percentage reduction in the amount of N released through mineralisation as a result of exclusion of different groups of soil fauna.
Source: Data derived from de Ruiter *et al.* (1993).

plant growth (Coleman *et al*., 1983; Wardle, 2002; Stockdale *et al*., 2006). Consequently, the role of soils as the organising centres within terrestrial ecosystems has been emphasised by some authors (Coleman *et al*., 1998). Russell (1937) clearly presented an integrated understanding of soil fertility, though he recognised that each specialist area has been tempted to claim the key to managing soil fertility for itself. Soil ecologists have not been exempt from this temptation: trophic interactions between soil organisms have been used as the sole basis of models of nutrient flows in soils; e.g., Brussaard *et al*. (1996) found that soil fauna can account overall for 30–40% of net N released into plant available forms (Table 3.1).

The agricultural intensification that occurred in the last half of the twentieth century in much of the world largely disregarded the biological interactions within the soil (Giller *et al*., 1997). Despite this, Giller *et al*. (1997) found limited evidence for any significant loss of either biodiversity or capacity for ecosystem function in soil. Wardle *et al*. (1999) studied the impact of agricultural intensification over 7 years and also found little evidence that intensification has adverse consequences for soil biological activity. This is not to say that farm management practices do not affect below-ground biological interactions both directly and indirectly through physical and chemical changes (Stockdale *et al*., 2006; Figure 3.4a, b): there is evidence that agricultural systems are associated with simplified food webs in the soil compared with semi-natural systems, and differences occur between agricultural systems that are predominantly pastoral or arable (van der Putten *et al*., 2004).

Stockdale *et al*. (2006) placed an ecosystem-driven model at the heart of soil function. This conceptual model recognised that below-ground processes, which contribute to the delivery of important functions, result from the emergent soil ecosystem properties and processes arising from the interaction of soil habitats and their associated populations. An integrated understanding of soil fertility therefore requires a consideration of the interactions between roots, soil organisms and their habitat within the soil (Figure 3.5). The relative

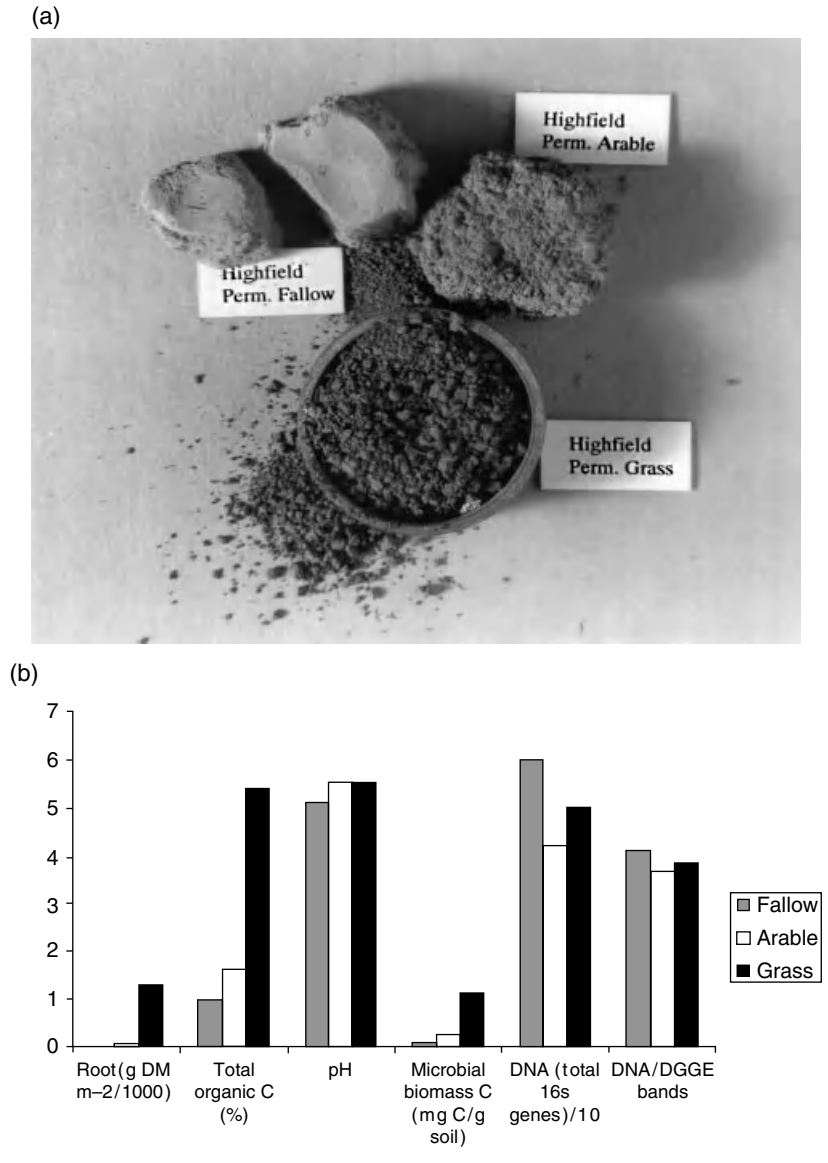


Figure 3.4 Data from the long-term Highfield experiment at Rothamsted, England, shows the impacts of long-term fallowing with intensive cultivation on (a) visible soil physical properties and (b) on some chemical and biological properties. The almost zero inputs of organic carbon via plants and tillage in the fallow plots has very significantly reduced soil organic carbon levels and soil microbial biomass but had no impact on pH in this well-buffered clay soil. Soil microbial diversity indicated by the number of bands in the DNA/DGGE is not reduced by fallowing; in fact, underlying soil microbial diversity is apparently revealed when the dominance of plant-associated bacteria is reduced. From Hirsch et al. (2009). With kind permission from Elsevier. For a colour version of this figure, please see Plate 3.1.

importance of abiotic factors (climate, management, inherent site constraints) in controlling the biological interactions and driving soil processes at a range of scales is still poorly understood (Bardgett, 2002). For soil fertility, increased understanding of the interactions driving soil water balance, nutrient cycling, rooting conditions and the regulation of soil-borne

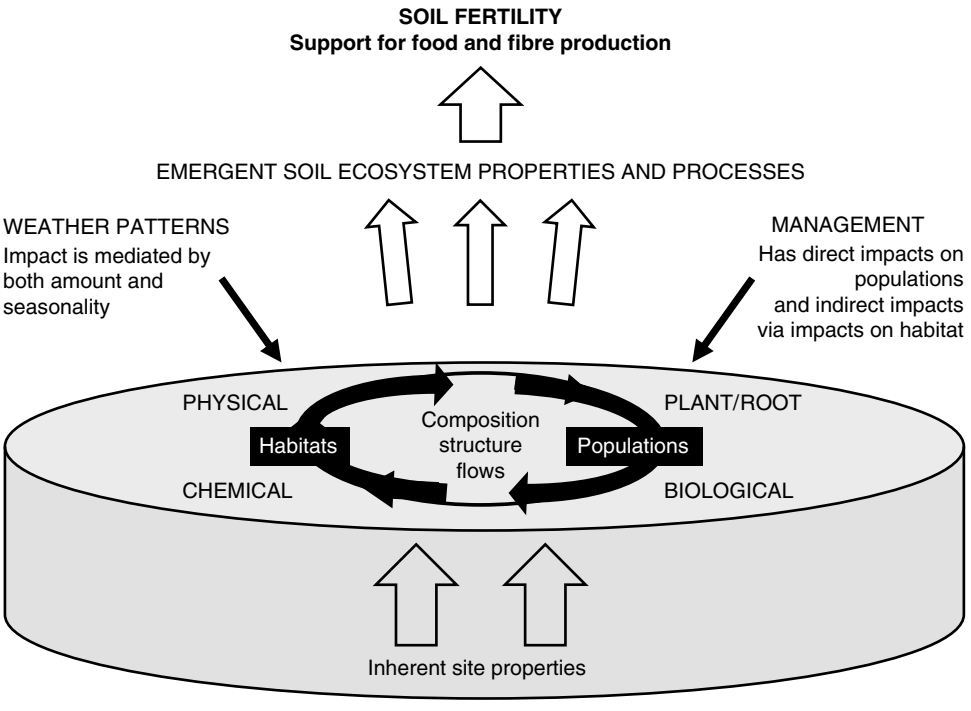


Figure 3.5 Soil ecosystem functioning is the result of physical, chemical and biological interactions between roots, soil organisms and their habitat within the soil. The interactions are driven by climate and management factors within the framework of permanent constraints set by the inherent site characteristics. The structure, composition and flows between soil populations and habitats determine the emergent properties together with the outcome and rate of soil processes observed at the soil scale. The outcome of these ecosystem processes is the soil functions which underpin all aspects of soil quality. For soil fertility, the interactions modifying nutrient and water availability, the environment for rooting and the activity of soil-borne pathogens are critical.

plant pathogens seem most important (Stockdale *et al*., 2006). A mechanistic understanding of such interactions is needed if management practices are to be robustly evaluated (Brussaard, 1998) and developed in a way that protects the ecosystem functioning at the heart of soil fertility.

Sanchez (1994) considered that the underlying rationale of soil fertility management, i.e. every constraint should be overcome through external inputs, was outdated and highlighted the need to replace this with a second paradigm to underpin soil fertility research which increased focus on the use of endogenous processes and potentials within the soil-plant system. We recommend taking an integrated ecosystem approach to the definition of soil fertility and that research into soil–plant interactions, which ultimately allow crops to grow and produce optimum yields, will be the focus for the twenty-first century rather than separate studies of soil processes in the absence of plants and/or processes in the plant root in the absence of soils. As illustrated in Figure 3.2, a wide range of plant and soil properties interact to affect nutrient supply to and uptake by plants. The study of any of these factors without an understanding of the ecosystem context in which they take place may limit the application of increased understanding to the improvement of soil fertility management in practice. Similarly for soil-borne pathogens, van der Putten *et al*. (2009) highlight how

modelling above- and below-ground plant–pathogen interactions could lead to new avenues for sustainable control of pests and diseases in crops, above- and below-ground pest and disease suppression, increased roles for arbuscular mycorrhizal (AM) fungi in plant nutrition and improved crop productivity.

3.3 Plant–soil interactions determining soil fertility

3.3.1 Impacts of soil on plant roots

Soil factors control plant growth largely through their impact on plant roots; in annual cropping systems, plant roots occupy relatively little of the soil volume (5–10%), whereas in grasslands it can be up to 40% of soil volume. The supply of water and nutrients to support plant growth critically depends on uptake from the soil across root membranes, so any factor that impedes plant root growth will impact water and nutrient uptake and apparent soil fertility. The rate of supply of nutrients to any root depends on the rates of mass flow and diffusion, but of critical overall importance for water and nutrient uptake is the distribution of roots within the soil, i.e. the total surface area over which uptake can occur. Root growth shows responses and interactions with a range of chemical, physical and biological factors in the soil (Hodge, 2006). In turn, many of these interact and plants are often able to compensate, so that restricted root growth in one part of the soil may be compensated for by increased growth in other regions that are less constrained.

The ability of the plant root to find space in which to extend through the soil is often an important factor limiting plant growth. The preparation of seedbeds with a good structure ('tilth') and consequent network of pores, holding the right balance of air and water appropriate to the seed to be sown, is an art underpinned by the science described in Chapter 8. The effects of soil compaction on root growth are also reviewed in Chapter 8; compact zones with high bulk density may restrict root penetration and radial growth of roots and so may reduce yield. The root cap perceives touch stimuli, and roots have also been shown to modify their gravitropic growth to avoid obstacles (Massa and Gilroy, 2003). Soil pore size and organisation together with water inputs to the soil determine soil water content (Chapter 9). The range in soil water content within which plant growth is not constrained by matric pressure, aeration or mechanical resistance (the least limiting water range; Da Silva *et al*., 1994) is therefore one indicator of soil fertility.

The amount, form and distribution of nutrients or toxic elements in soil also influence the amount and distribution of root growth. Root branching may also be regulated by external nutrient concentrations with local stimulation of lateral root growth observed in zones of high N, P and potassium (K) availability (Drew, 1975; Forde and Lorenzo, 2001), though not all plants respond in the same way (Hodge *et al*., 1998). Plants will usually selectively avoid rooting into zones of high toxicity. For example, in most plants, the first visible symptom of aluminium stress (often linked with acid conditions) is the inhibition of root elongation (Matsumoto, 2002); consequently rooting depth is often restricted by acid subsoils. Similar restrictions to rooting are seen where soils are saline or have boron toxicity. Under conditions of nutrient deficiency or toxicity, a range of specific physiological changes take place caused by multigenic interactions (Figure 3.6); e.g., over 1000 genes are differentially regulated under conditions of P starvation in Arabidopsis (Hammond *et al*., 2003; Wu *et al*., 2003; Morcuende *et al*., 2007). Understanding the transcriptional regulation of these genes can allow the identification and selection of genotypes that are better suited to cope with conditions of low nutrient availability or elevated concentrations of potentially

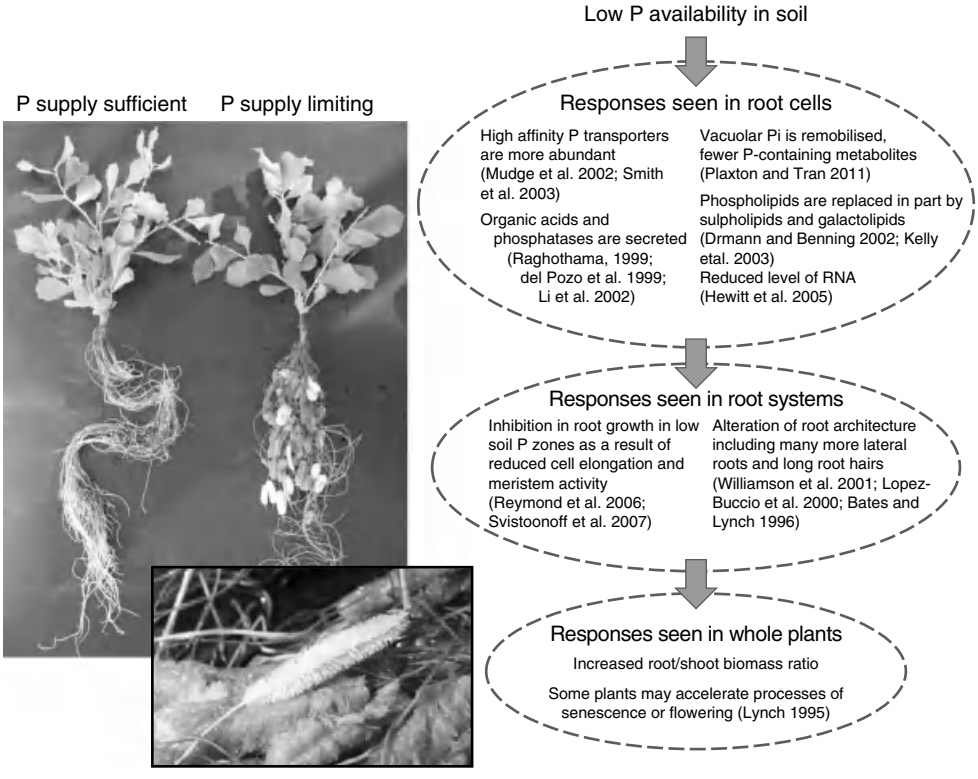

Low P availability in soil
P supply sufficient
P supply limiting
Responses seen in root cells
High affinity P transporters are more abundant (Mudge et al. 2002; Smith et al. 2003)
Organic acids and phosphatases are secreted (Raghothama, 1999; del Pozo et al. 1999; Li et al. 2002)
Vacuolar Pi is remobilised, fewer P-containing metabolites (Plaxton and Tran 2011)
Phospholipids are replaced in part by sulpholipids and galactolipids (Drmann and Benning 2002; Kelly etal. 2003)
Reduced level of RNA (Hewitt et al. 2005)
Responses seen in root systems
Inhibition in root growth in low soil P zones as a result of reduced cell elongation and meristem activity (Reymond et al. 2006; Svistoonoff et al. 2007)
Alteration of root architecture including many more lateral roots and long root hairs (Williamson et al. 2001; Lopez-Buccio et al. 2000; Bates and Lynch 1996)
Responses seen in whole plants
Increased root/shoot biomass ratio
Some plants may accelerate processes of senescence or flowering (Lynch 1995)

Figure 3.6 Complex and interlinked changes in plant physiology at root cell, root system and whole plant scales occur in response to low P availability in soil as the result of up-regulation of many genes. Photographs show *Hakea prostrata* R. Br. grown under sufficient and limiting phosphate supply. Cluster roots develop in some species as an adaptation for P acquisition in low P environments (details in lower image). Thanks to Stuart Pearse and Michael Shane from the University of Western Australia for access to greenhouse trials which provided the photographs. For a colour version of this figure, please see Plate 3.2.

toxic elements; it may also allow the use of transcriptional arrays to identify nutritional deficit or toxicity far in advance of any physical symptoms (Hammond *et al*., 2004).

Direct damage to plant roots by root feeding and parasitic organisms can be considerable (particularly by beetle larvae and nematodes) and can therefore limit the extent to which roots exploit the soil volume. In addition, a wide range of soil micro-organisms that can cause plant disease through root invasion, in particular soil fungi, have been identified and their ecology described (for detailed descriptions see, e.g., Bruehl, 1987). Interactions between the plant species, soil organisms and environmental conditions determine infectivity with regard to the host crop (Smith *et al*., 1999). Some soils have been shown to be disease suppressive (Menzies, 1959); a wide range of ecological mechanisms (including parasitism, direct and indirect antagonism) are now thought likely to contribute to this effect (Mazzola, 2002) and interactions with soil chemical and physical properties are also important (Duffy *et al*., 1997).

3.3.2 Association and symbiosis between plant roots and soil organisms

The majority of plants are capable of forming mycorrhizal associations with various soil fungi (see Chapter 11). The most common is the AM association, which has been shown to have

emerged very early in the evolution of land plants (Remy *et al*., 1994). Developments in molecular and transcriptional analysis in recent decades mean we now understand a lot about the molecular responses of non-mycorrhizal plants to nutrient deficit, primarily due to the focus of transcriptional studies on the model plant *Arabidopsis*. Unfortunately, very little is known about such responses in mycorrhizal plants, which make up 90% of all land plant families; only very few crop species do not form such associations, among them *Brassicae* and Chenopodiaceae. Over 60 years ago, Sir Albert Howard suggested that 'the presence of an effective mycorrhizal symbiosis is essential to plant health' (Howard, 1943). The wide benefits of mutualistic relationships in an AM association to crop nutrition, health, stress resistance and the development of soil structure have since been confirmed and the impacts of management on their infectivity and effectiveness studied, e.g. Bethlenfalvy and Lindermann (1992), Harrier and Watson (2003) and Gosling *et al*. (2006). Most soils have indigenous populations of AM fungi, but more work is needed to understand whether and how these associations can be manipulated to support integrated soil fertility management approaches.

The nitrogen-fixing symbiosis that exists between plants of the Leguminosae (legumes) and the soil heterotrophic bacteria, known generally as rhizobia, has been understood for over 100 years (Atwater, 1884; Hellriegel and Willfarth, 1888). There are a number of other nitrogen-fixing associations between soil micro-organisms and plants, those involving cyanobacteria and those in which the microbial partner is an actinomycete, which are important in natural and in agricultural systems. Rhizobia are a phylogenetically disparate group of α- and β-proteobacteria; more than 70 species have been identified (Masson-Boivin *et al*., 2009). Nodule formation in legumes occurs as a result of complex interactions between plant and microbial processes whose biological, biochemical and genetic aspects have been much studied (Sprent, 2001; Masson-Boivin *et al*., 2009). The precise details of nodule formation are still not fully understood (Martinez *et al*., 1990; Brewin, 1991; Povorov, 1998), although research into signalling and host plant cell responses during infection by rhizobia or arbuscular mycorrhizae (Oldroyd *et al*., 2009) has suggested that it may be possible to induce colonisable nodules on plants other than legumes. Rhizobia–legume interactions have been shown to be highly specific (Long, 2001) and a wide variety of morphological variations have been observed. McInnes and Haq (2003) reported the impact of a wide range of environmental, plant (host and non-host) and soil (physical, chemical, biological) factors on the persistence and effectiveness of rhizobial populations in the nodulation of legumes. Even where nodulation is effective, the achievement of high rates of nitrogen fixation depends on a very complex mixture of interactions including the plant, the bacteria species, and climatic and soil factors (Peoples *et al*., 2009). At the practical interface with agriculture, agronomists still struggle even to give broad ranges of N fixation associated with any particular species of crop or forage legumes, let alone give a site-specific estimate on which a rotational fertilisation plan can be based (Smil, 2001; Unkovich and Pate, 2001; Herridge *et al*., 2008).

The development of molecular technologies is increasing the number of effective plant–microbial interactions that have been identified and understanding of their modes of interaction (Berg, 2009). Much of the work on these interactions to date has focussed on the understanding of the mechanism and possible isolation of the key organisms involved. Hayat *et al*. (2010) identify three main modes of action for plant growth promoting rhizobacteria (PGPR) species: (1) synthesising particular compounds for the plants, (2) facilitating the uptake of certain nutrients from the soil and (3) lessening the impact or protecting plants from diseases. A number of plant growth promoting fungi (PGPF) have also been isolated belonging to the genera *Trichoderma*, *Fusarium*, *Penicillium*, *Phoma*, etc. and have been

reported to be beneficial to several crop plants, not only by promoting their growth but also by protecting them from disease (e.g. Shivanna *et al*., 1996; Harman, 2011a). Trichoderma has been known as a fungal biocontrol agent for many plant diseases since the early twentieth century, although the mechanisms of action were not known. Much or most of the biocontrol activity of these fungi is now considered to be a result of their ability to induce systemic disease resistance, and effective strains also convey stress resistance to plants (Harman, 2011b). The basidiomycete *Piriformospora indica* has at least qualitatively similar effects on plants (Shoresh *et al*., 2010), and hence it has been suggested that mixed species approaches might have greater impact. Ardanov *et al*. (2011) suggest that there may be an important difference between endophytic bacteria which are able to activate basal and inducible plant defence systems and biocontrol strains which have a plant growth promotion effect which is not correlated with induced resistance.

Plant growth promotion arising from interactions between soil organisms and plant roots is complex and often cannot be attributed to a single mechanism; it may result from the synergistic interactions of a number of species, not only soil bacteria or fungi (Richardson *et al*., 2009). For example, many reports have documented the ability of soil micro-organisms (such as *Pseudomonas*, *Bacillus* and *Rhizobium* spp., actinomycetes and various fungi such as *Aspergillus* and *Penicillium* spp.) to solubilise insoluble mineral phosphate compounds (Richardson *et al*., 2009). The most common mechanism used by micro-organisms for solubilising mineral phosphates in neutral and alkaline soils seems to be acidification and Ca-chelation via biosynthesis and release of a wide variety of organic acids (Whitelaw, 2000 and Chapters 5 and 11). However, attempts to improve mineral phosphate solubilisation by inoculation with isolated P-solubilising bacteria and/or fungi have not been particularly successful because of limitations such as poor ecological fitness, low metabolite production, variability in inoculant-delivery systems and inconsistent performance in field applications (Shenoy and Kalgudi, 2005; Richardson *et al*., 2009).

3.3.3 Impacts of plants on soil

While soil properties have a role in controlling root distribution, plant roots also play a key role in soil structural development; roots are the most important agents creating structural pores in undisturbed soils. Roots expand by forcing a root tip into pores of 100–300 μm diameter. The young root then tends to compress soil around the pore by radial expansion, increasing the size of the pore occupied by the root but decreasing porosity and modifying pore size distribution in the rhizosphere; in the medium term, rooting tends to increase soil macroporosity through the provision of stabilised continuous channels (Angers and Caron, 1998). Differences between crops in their impact on soil structure have been noted, in part as a result of the fact that crops differ in the patterns and depth of rooting (Gregory, 2006; Chapter 10). While plant roots use pores of >100 μm diameter as points of entry, they can effectively empty pores down to 0.2 μm; this increases differences in the depth and patterns of soil wetting and drying.

The zone of soil in the immediate vicinity of the root is markedly different in its properties to the remainder of the soil as a result of the direct impacts of plants on the soil (Table 3.2). In 1904, Hiltner first used the term ‘rhizosphere’ for this interfacial zone between the plant roots and the bulk of soil, and this term is now used widely for the zone of soil surrounding the root within which the soil is directly affected by the presence of the root. The rhizosphere is a dynamic transit zone, with large fluxes of water and plant nutrients across it, and consequently small pool sizes for most nutrients, driven by patterns of plant demand and uptake (for more detail see Chapter 10).

Table 3.2 The rhizosphere has markedly different physical, chemical and biological characteristics than bulk soil which is not under the direct influence of plant roots.

Soil characteristic and observed change in the rhizosphere	Reference for paper where an example of these differences can be found
Water retention properties	
Smoother, less convoluted pores; larger pores on average	Whalley *et al.* (2005)
Nutrient availability	
Five- to tenfold accumulation or depletion depending on the balance between mass flow and uptake at the root surface	Marschner (1995)
pH	
Changes of 2–3 pH units (100–1000-fold difference in proton concentration); both increases and decreases in acidity of this magnitude are seen in the rhizosphere depending on plant species and management particularly the form of N taken up by the plant; uptake of N as NH_4 leads to proton excretion and is acidifying, NO_3 tends to increase pH	Neuman and Römheld (2002)
Redox conditions	
Reductase capacity can be increased up to 100-fold in the rhizosphere	Römheld (1990)
Labile organic matter	
Sugars and amino acids increased by 2–10 times in the rhizosphere as a result of root exudation	Uren (2000); Jones *et al.* (2004)
Microbial populations	
10- to 100-fold increase in microbial activity with particular stimulation of gram –ve bacteria in the rhizosphere but reduction in microbial diversity	Chineau *et al.* (2000); Kowalchuk *et al.* (2002)
Soil fauna	
Marked increase (around tenfold) in bacterial grazers (nematodes, protozoa, microarthropods)	Griffiths (1994); Bonkowski *et al.* (2000)

The amounts and composition of root exudates are the main driver for the large increase in size of the microbial biomass and change in the structure of communities of soil organisms found in the rhizosphere. For example, species-specific flavonoids have been identified as key signalling compounds in plant–micro-organism interactions (Shaw *et al.*, 2006). Distinct communities of bacteria have been found within the plant root and on the root surface (rhizoplane; Lupwayi *et al.*, 2004; Dennis *et al.*, 2009); around 4–10% of the root surface has been shown to be covered by soil micro-organisms. Some soil organisms stimulated in the rhizosphere are plant pathogens, and there is evidence that bacterial as well as fungal pathogens have co-evolved with plants showing a high degree of host specificity (Raaijmakers *et al.*, 2009). Plants are not the passive recipients of a pre-existing rhizosphere community that merely feed on root exudates: a series of interactions between plants and soil factors determines the structure and function of the associated rhizosphere community (Berg and Smalla, 2009).

Plants regulate and exclude elements and molecules at the root surface, manipulating the rhizosphere in a range of ways (changing pH and redox potential, hydraulic lift, exudation and secretion of organic acids and enzymes) in order to tolerate toxicities or deficiencies or manipulate microbial communities (Chapter 10). All such traits are controlled by specific genes or cascades of genes, some of which have been identified but many of which are still to be elucidated. Once understanding of the genetic control is gained, it may be possible to manipulate the rhizosphere directly by deploying crops and/or varieties in which the gene of

interest is expressed, within appropriate crop rotations. Much potential exists to manipulate rhizosphere properties at a genetic scale, but such attempts need to be informed by an understanding of the controls imposed by the complex soil environment in which they need to be effective (George *et al*., 2004, 2005).

3.4 Assessing soil fertility

Assessment of soil fertility takes place within the context of an individual farming system, where the crop choice and crop yield and quality goals are largely defined by constraints arising from societal policies, laws and financial incentives, economic costs and the aspirations, attitudes, education and training of the land manager. In the twentieth century, the assessment of soil fertility focussed on the assessment of the need for a range of external inputs that were used to overcome the identified soil constraints. Socio-economic factors also interact with the physical constraints arising from climate and location characteristics; together these constraints also determine which, if any, management strategies are available for soil fertility management. Towards the end of the twentieth century, increased awareness of the environmental impact of agriculture led to policies and legislation in a number of countries limiting the amount and/or timing of inputs, such as fertiliser and manure applications, and cultivations, such as ploughing grassland.

During the mid-late twentieth century, the use of fertilisers to overcome nutrient limitations to crop production expanded greatly, and fertiliser purchases are now a major part of the variable costs of production in most cash-cropping systems worldwide. Alongside these changes in management, developments in soil fertility assessment were focussed on the measurement of soil nutrient status to guide the development of recommendations for lime and fertiliser application to crops (Tisdale and Nelson, 1966; Cooke, 1982; Foth, 1997). Thousands of pot and field experiments have been conducted to evaluate soil fertility (i.e. given conditions x, how well does the plant grow, take up nutrients and water, produce grain/fruit) and to establish management recommendations for inputs of fertiliser, animal manures or lime (i.e. given conditions x, with an addition of y, a yield increase of z can be expected). However, in many developing countries, the adoption of such intensive input-focussed systems has not occurred to any great extent, in part because high yielding varieties, fertilisers and pesticides can be difficult to obtain due to poor distribution infrastructure and hence high costs. A range of renewable soil fertility replacement strategies have been proposed that are suitable for low-input systems (Ajayi *et al*., 2007). For instance, significant attention has been given to the development of legume agroforestry (fertiliser tree) systems, the integration of green manure and dual purpose legumes and the careful use of animal manures often integrated into conservation farming approaches; the latter integrate reduced tillage, retention of crop residues, targeted planting and farm input use and the use of legumes in the rotation (Sanchez and Salinas, 1981; Palm *et al*., 2001).

Increasingly in industrialised countries, farming systems are required to deliver broader societal goals, e.g. protection of wildlife habitat and/or seek alternative sustainable approaches, e.g. through certification to organic farming standards. Consequently, there has been an increased focus on practices and technologies that optimise inputs, make better use of existing soil nutrients and minimise the leakage of nutrients, especially N and P, from farms to the wider environment. This has seen farm nutrient management planning shift from a relatively small set of procedures designed to optimise fertiliser application rates for crop and animal production towards comprehensive whole-farm nutrient management

approaches that consider a range of issues to deliver both farm productivity and environmental outcomes (Goulding *et al*., 2008). In the twenty-first century, alongside predicted changes to climate, including the increasing frequency and intensity of extreme weather events, it seems almost certain that fossil-fuel-based inputs, such as N fertilisers and pesticides, as well as other non-renewable resources such as P fertilisers, will become increasingly expensive and scarce. These constraints are likely to necessitate the adoption of changed practices within intensive input-focussed farming systems (Kirschenmann, 2007). Consequently, the uptake of practices such as carefully planned crop rotations, maintenance of soil organic matter and the recycling of local organic 'wastes' is likely to increase in all farming systems (Hanson *et al*., 2007) and be integrated with new approaches developed for lower input conditions. Within such systems, a broader integrated approach to the assessment of soil fertility that considers the integration of soil physical, biological and chemical aspects, together with inputs of water and nutrients from a range of sources, will be needed. It is therefore timely to review the assessment of soil fertility in this context.

3.4.1 Assessment of soil fertility and fertiliser requirements

The mere analysis of soil properties, however carefully selected, does not give a measure of soil fertility unless the selected parameters have been calibrated against plant growth. In yield response experiments, the aim is to describe the relationship between crop yield and increments of a nutrient or, in a factorial experiment, to measure the response to two or more treatments in combination. When carried out in the field, such an experiment can be used to assess the relative importance of limiting factors to crop yield at the site (Table 3.3) and may also allow the optimum soil fertility management strategy (cultivations, crop residue management strategies, inputs of organic matter, nutrients, water, lime) under the conditions of the experiment to be identified. The results for a single combination of crop, site and management factors are of very limited use alone. Consequently, farmers or their extension officers may need to carry out site-specific on-farm research to identify optimum system-adapted soil fertility management approaches. Additionally, by grouping results from similar soils and crops, it may be possible to draw out guidelines, whereby a set of measures of soil properties provide an index of soil fertility, which support the farmer to select from a limited range of soil fertility management strategies to obtain optimum economic benefit. For example, this approach has been used over many years to create and adapt the UK *Fertiliser Manual (RB209)* (Defra, 2010).

A number of steps are critically important in any system used to support the practical management of soil fertility:

1. Analysis of selected soil properties which have been shown to correlate with crop yield, nutrient uptake or quality.
2. Interpretation of the results to predict the degree of yield constraint as a result of expected deficiency of nutrient supply or intensity of some other constraint, e.g. compaction.
3. Development of recommendations for appropriate fertiliser, manure or other crop management practices that will enable yield optimisation.

The effective performance of any soil fertility assessment system also relies on the fact that the sample points measured in the field or presented for analysis are representative. More, deeper and perhaps more frequent, soil samples are needed for more mobile nutrients (e.g. nitrate, sulphate) or constraints (e.g. salinity). Hence, great care is taken as part of

Table 3.3 Bivariate regression of wheat grain yield with a range of weather, agronomic and soil physical, chemical and biological properties for 40 paddocks in each of two study areas (A and B) in Western Australia.

		Area		Coefficient[a]	P-value[b]	% variability
	Attribute	**A**	**B**			**explained[c]**
Climate	Rainfall (mm)	211[a]	206[a]	–	ns	3.7
Agronomy	N fertiliser (kg N ha^{-1})	20[a]	24[a]	0.02	0.055*	9.4
Physical	Clay content[d] (%)	11.0[a]	10.4[a]	0.08	0.062*	9.1
Chemical	Total carbon (t C ha^{-1})	9.0[a]	10.8[b]	–	ns	0.2
	pH ($CaCl_2$)	5.7[a]	5.6[a]	–	ns	0.4
	EC[d] (mS m^{-1})	80[a]	63[b]	–	ns	0.1
Biological	Labile C (kg C ha^{-1})	83[a]	118[b]	0.01	0.041**	10.5
	Microbial biomass C (kg C ha^{-1})	107[a]	183[b]	0.01	0.001***	30.3
	PMN (kg N ha^{-1})	7.0[a]	10.1[b]	0.14	0.003***	21.2

Average grain yield was 1.76 and 3.24 t ha^{-1} in areas A and B, respectively. Mean values of attributes that contributed significantly to the explanation of wheat grain yield are presented; attributes followed by the same letter are not significantly different between the two areas. Several soil attributes were identified that did not have a significant (direct) influence on grain yield; but may have had an indirect influence through their effect on the size of the microbial biomass. In this case, 66% of the variability in microbial biomass could be explained by clay content (log transformed data), pH and labile carbon.

[a]The coefficient can be interpreted as t ha^{-1} grain yield change per unit change in attribute.

[b]The variability explained has a maximum of 100% and is not additive between individual attributes. Using a multiple regression model that included all parameters listed in the table, we were able to explain 42% of the yield variability.

[c]Clay and EC data were assessed using robust regression analysis due to unusual data points. EC, electrical conductivity.

*Significant at $P < 0.10$;

**Significant at $P < 0.05$;

***Significant at $P < 0.01$.

ns, not significant.

Source: Unpublished data provided by D.V. Murphy.

fertiliser recommendation systems to give clear guidance on the pattern, depth, timing and frequency of sampling (Sabbe and Marx, 1987; Defra, 2010); such recommendations are fitted to different land use types and perhaps even different cultivation methods; e.g., increased use of no-till approaches requires careful attention to the depth of samples taken as increased profile stratification is seen in no-till systems (e.g. Ismail *et al*., 1994). Increased potential precision in fertiliser application, through the use of machinery guided by global positioning systems, has led to an increase in the use of nutrient mapping within fields on large, intensive farms. Such 'Precision Farming' needs to be underpinned by a good understanding of the spatial variability of the inherent soil characteristics such as texture and an appreciation of the many factors that control soil fertility and crop growth and yield. Farmers that use precision farming techniques value them for things such as savings in fertiliser costs (minimal overlapping during application). However, Anderson-Cook *et al*. (1999) showed no significant advantage in detailed grid sampling approaches compared to the use of stratified sampling approaches designed with an awareness of soil-type patterns to guide

P and K fertiliser recommendations for precision farming approaches, especially given the significantly increased costs associated with the collection and analysis of soil samples in most grid sampling approaches.

3.4.2 Role of plant analysis for soil fertility assessment

Where long-term assessment of soil fertility is required or where plant stress can be addressed by management within the growing season, plant analysis rather than soil testing may provide an appropriate indicator of soil fertility. Within-season testing of plant tissues at particular growth stages may permit fertiliser treatments to be used to address critical deficiencies which otherwise might limit yield (Walworth and Sumner, 1986). For example, Havlin *et al*. (1999) provide a clear summary of the use of plant tissue testing to guide in-season fertiliser for a wide range of crops within the USA. The availability of soil nutrients to a plant is determined both by the nutrient absorption capacity of the plant root and nutrient supply and retention characteristics of the soil. Consequently, post-harvest analysis of yield and nutrient concentrations in crops allows the evaluation of the integrated impact of both plant and soil processes and the efficacy of soil fertility management, given the actual yield, weather conditions and achieved management interventions (all of which may differ from what had been planned).

'Smart plants' have been developed under research conditions and it may become practical to use them in the field to diagnose nutrient deficiencies or growth limitations due to other constraints, e.g. acidity, in real time. Such plants are genetically engineered by transformation with constructs containing the promoter of a gene up-regulated specifically under the target condition (e.g. P deficiency) in an accessible tissue. For example, Arabidopsis bearing such a construct showed increased β-glucuronidase activity was linked to a green fluorescent protein signal molecule and was detectable, using confocal microscopy, when P was withdrawn from solution culture before growth was limited (Hammond *et al*., 2003). Hence, such 'smart plants' could have the potential to monitor plant response to previously identified limiting constraints and allow targeted precision management within the growing season before the limitation becomes a problem.

3.4.3 Soil analysis

While plant nutrient concentrations are useful post hoc evaluation tools, they are of little use for the advanced planning of nutrient applications to annual crops. Soil analysis can be used to provide an indication of soil fertility before any crop is planted and hence support the planning of the season's management tactics as well as supporting long-term monitoring of soil fertility and the effectiveness of soil fertility management strategies. Which soil properties should be analysed to give a good indication of soil fertility? Put simply, those which indicate characteristics that need to be understood or modified to achieve optimum yield, namely rooting conditions, water supply, nutrient supply and risk from soil-borne pathogens. However, the identification of simple robust measures that correlate closely with nutrient uptake and crop yield for all climates, crops and soil types has proved to be problematic. In part, this is a result of the complex interaction of limiting factors and constraints to crop growth in the field (Figure 3.1).

Scientific selection of indicator measurements for soil fertility requires that they can be measured easily and economically, as well as accurately and precisely, across a wide range of soil types and soil conditions and that they are based on reliable and contemporary

scientific knowledge (Brookes, 1993; Stenberg, 1999). The appropriateness of the indicators chosen for soil fertility assessment depends on how well they are understood with respect to the agricultural system of which they are part and, consequently, how well they can be used to guide on-farm management decisions (Lal, 2001). To date, crop responses to soil nutrient contents (and additions) and soil acidity have generally been studied more intensively than crop responses to physical condition, levels of soil organic matter and other biological indicators.

As described in Chapter 2, the uptake of nutrients by a plant is a result of both the root absorbing power and the nutrient concentration in the soil solution; both plant and soil factors are important. The key soil factors affecting nutrient cycling in soil and supply to plants are discussed in detail later (for N see Chapter 5). However, soil solution concentrations can be difficult to quantify accurately due to very small pool sizes. In addition, determination of the concentration of nutrients contained within the soil solution on one occasion has often proved to be very weakly predictive of plant growth across the season (e.g. Murphy *et al.*, 2009). This is because soil solution concentrations are dynamic, changing from day to day, and because the buffering capacity of the soil solid phases in relation to each nutrient is critically important in determining the rate at which nutrients in the soil solution can be replenished. For example, snapshot measurements of soil mineral N (NO_3^- and NH_4^+ in solution and NH_4^+ held on soil surfaces) can only give a partial prediction of soil N supply for crop growth, since the bulk of soil N is found in organic forms; as part of a long-term monitoring scheme, the average amount of mineral N measured in topsoil during autumn in the UK was only 76 kg N ha^{-1} compared to 7000 kg N ha^{-1} in organic matter (Shepherd *et al.*, 1996). The interlocking biological processes controlling N supply from soil organic matter (e.g. mineralisation, immobilisation, nitrification, denitrification) resulting from the interaction of soil organisms, physical, chemical and biological characteristics modified by interactions with plant roots, weather and management are still not fully understood. As such, seasonal patterns of N availability remain difficult to predict and thus include in fertiliser decision support systems.

The development of methods for assessing the size of the pool of available plant nutrients for the next season of growth has usually focussed on developing an extraction procedure which removes a 'labile' pool and which integrates a measure of pool size and rate of supply. However, no single method can simulate these complex dynamic processes and so measurements of 'available soil nutrients' are usually selected based on correlation with plant growth in otherwise non-limiting conditions. In most countries one or two tests are favoured; in many cases, the tests which are used are as much a matter of the history of their development as of rigorous comparative scientific evaluation. For example, the determination of K availability is usually directly linked to the determination of exchangeable K; a number of extractants are considered to be equally effective in displacing K from the exchange complex (Munson, 1985; Syers, 1998). In contrast, a large number of tests to assess available soil P are in use around the world. The extractants used vary in their strength and mode of action (Sibbesen, 1983). No single test is suitable for all soil types and few routinely used tests give information about the availability of organic forms of P in soil. Because of the multiplicity of methods, there is increasing interest in the development of on-the-go analyses using a range of sensing technologies. Several such approaches are now at proof-of-concept stage (as reviewed by Sinfield *et al.*, 2010) to provide information on soil physical, chemical and biological properties rapidly in the field to support immediate, spatially variable applications of lime and/or fertiliser. Spatial patterns of some soil properties can be determined by mid-infrared sensors (Janik *et al.*,

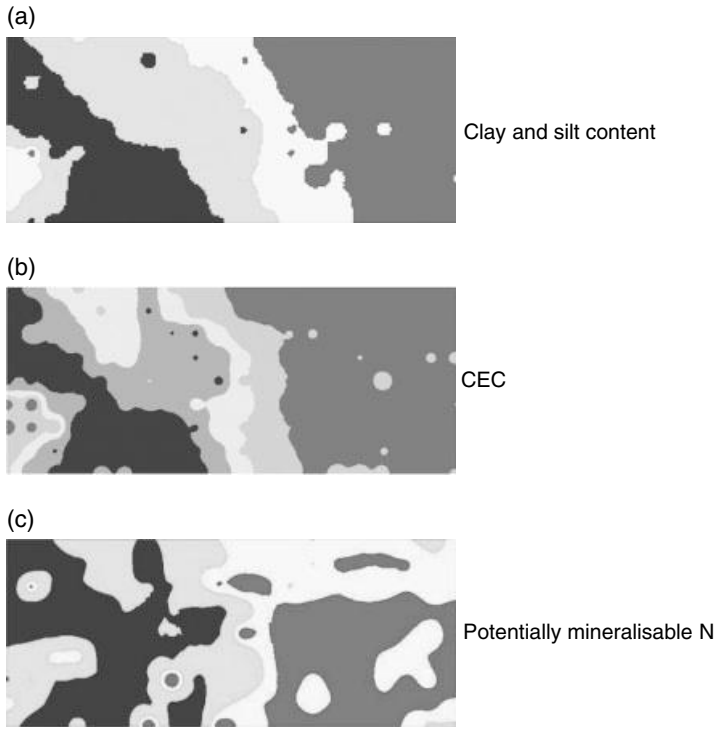
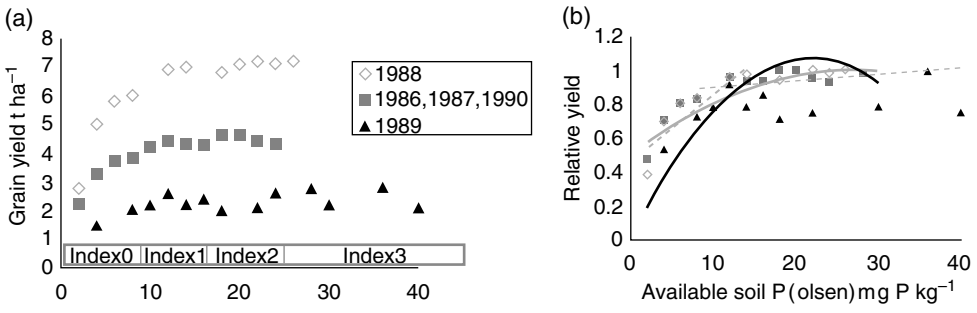


Figure 3.7 Spatial maps of (a) clay and silt content, (b) cation exchange capacity and (c) potentially mineralisable N (where the colours show quartiles ranges as an illustration) over a 10 ha area (200 × 500 m; 180 sampling points on a 25 × 25 m grid) where the properties were determined using mid-infrared sensors. The spatial patterns were very strongly correlated with the same properties determined by traditional laboratory-based methods ($r^2 = 0.91$, 0.91 and 0.82, respectively). Unpublished data from the central wheatbelt, Western Australia, provided by D. V. Murphy. For a colour version of this figure, please see Plate 3.3.

1998; Figure 3.7a–c). This technology has the potential to be incorporated into rapid remote sensors that could be tractor mounted.

3.4.4 Interpretation of the results of soil analysis

The definition of justifiable target ranges or threshold values for soil nutrients and other properties relevant to soil fertility has also become a contentious issue in the development of interpretive frameworks to support soil quality monitoring (Arshad and Martin, 2002; Sparling *et al*., 2003). Most of the detailed work carried out on relationships between soil fertility and crop growth has focussed on the relationship between yield and nutrient supply. There are data for relationships with other chemical properties e.g., acidity, and data are increasingly available for relationships between yield and physical properties (see Chapter 8). However, relatively few data are available to define suitability limits for soil biological properties for different crops, with the exception of some soil-borne diseases. Empirical relationships between yield and constraints usually show a curve of diminishing returns, so that as the constraint reaches non-limiting status the response to change decreases. Hence, absolute targets or thresholds are difficult to determine objectively.



(c)

Fitted relationship (without constrained intercept) used from figure 3.8b	Available soil P (mg kg^{-1}) needed to achieve the target yield			
Operational relative yield	0.85	0.90	0.95	0.99
Curve	11.9	15.8	20.4	24.6
Two line fit (lines intersect at a relative yield = 0.898)	9.8	11.6	24.4	34.7

Figure 3.8 (a) Response of grain yield (t ha^{-1}) in spring barley to levels of available P (measured by bicarbonate extraction, Olsen) in a 5 year series of field experiments relating yields of spring barley to Olsen extractable P in the Hoos Barley Experiment at Rothamsted Research (silty clay loam soil) showing the critical ranges of soil P used to guide fertiliser recommendations, where Index 2 is considered the target range to provide sufficient soil P. (b) Response of grain yield for spring barley expressed as relative yield to normalise across years with available soil P. Response curves fitted to interpret the results and determine the optimal level of soil P using quadratic equations either with a constrained intercept = 0 (solid line) or a free intercept (dotted line) and with two straight lines with a free intercept (dotted line); these lines intersect at a relative yield of 0.898. In this case, the Olsen extract does not extract all plant available P; hence, it is not appropriate to constrain the responses to pass through the origin. (c) Soil available P values at a range of operational yield levels derived from the curve and straight line fits – operational yields of either 0.95 or 0.99 are commonly used to determine the optimum. Even small differences in the recommended level of available soil P can have large financial implications for the farmer; e.g., Defra (2010) indicates that increasing soil P by 10 mg kg^{-1} may need additional fertiliser applications totalling 850 kg ha^{-1} of triple superphosphate over a decade.

Sufficiency indices/non-limiting thresholds

Based on empirical observations of plant growth and yield responses to added nutrients, a common interpretation approach has been to categorise the range of nutrient availability into regions of low, adequate and high/excessive (Figure 3.8a). In the UK, this approach was used to develop the 'Index System' guidelines which provided an interpretation of soil test values with data from crop response experiments by Crowther and Yates (1941), and in the USA a similar approach was taken by Bray (1944, 1945, 1948). The use of relative yields in the analysis allows a better examination of the underlying relationship between soil supply and crop responses, even under different site and weather conditions (Evans, 1987). A range of curve-fitting approaches can then be used to support the interpretation of the data (Figure 3.8b). Because the Mitscherlich curve is asymptotic, the soil test value at a relative yield of either 0.99 or 0.95 is most often used to indicate the point at which there is no constraint to yield resulting from that nutrient under the typical management system in the field trials. The form of the response curve means that relative yields change slowly across

a wide range of soil test values (Figure 3.8c), and interpretation of the data to give sufficiency levels to inform management depends on the underlying assumptions used. When errors associated with individual field experiments are taken into account, there is often no significant difference between fitting two intersecting straight lines to the response graph rather than a curve (Boyd *et al*., 1976) as long as experiments are grouped by climate/soil/crop/management. The most appropriate interpretation approach also depends on the scientific understanding underpinning the development of the extraction methodology in the context of the soil-plant system; e.g., is the soil test effective in extracting all the available nutrient or does it extract only one part of plant available nutrient (hence, should the response curve be constrained to pass through the origin)? Hence decisions taken, when sufficiency ranges and thresholds are defined, are often more subjective than is realised. In the UK, expert groups (for P in 1962 and for K in 1963) were brought together to determine the most appropriate extraction methods for England and Wales and to identify soil test ranges linked to the likelihood of response to added fertilisers; the same ranges are still used in the current Fertiliser Manual (Defra, 2010; shown for P in Figure 3.8a) because no better, widely applicable method or framework for interpretation has been found. However, it is now important to consider whether, given the interactions of a number of constraints in the field and the increasing cost of inputs, it is still appropriate to set threshold values for all constraints at the highest relative yield levels with information derived from single factor response experiments. The same interpretative framework (sufficiency/non-limiting thresholds) can be used for calibration of multi-factor effects of soil constraints and management approaches – e.g., by using a response surface approach to support interpretation (Morton *et al*., 2001; Bossa *et al*., 2005).

The limiting factor/sufficiency approach can be applied to more than nutrients. For example, in Australia, recent developments in DNA-based assays, such as PredictaB® (South Australian Research and Development Institute), have enabled grain producers to determine inoculum levels of a broad range of soil-borne diseases before seeding and the data used to underpin decision support services for disease control such as the use of resistant varieties or a change in cropping patterns (Heap and McKay, 2009). Inoculum levels measured before sowing are usually correlated with root damage and crop biomass reduction and so can be interpreted as a disease risk rating. In most cases, high inoculum levels are expected to be associated with yield loss, but interactions during the growing season between weather conditions, crop nutrient status and soil type may confound this relationship (Heap and McKay, 2009).

Expert group approaches continue to be used to draw together a range of stakeholders with different focuses and expectations to define relationships for a wider range of soil properties and crop production systems and interpret them in terms of limiting or sufficiency ranges (Figure 3.9). Andrews *et al*. (2002) show how this was achieved for indicators of soil fertility in vegetable production systems in California and Lilburne *et al*. (2004) for indicators of soil quality in New Zealand. Participatory approaches with farmers are particularly important where the aim is to develop a scorecard for on-farm assessment and interpretation of soil properties affecting crop productivity (Romig *et al*., 1995).

The sufficiency concept is the most common framework used for interpreting soil analysis for soil fertility. Its foundation is Liebig's law of the minimum. It is intuitively reasonable to assume that through management (irrigation, fertiliser, cultivation, etc.) the soil can be modified so that no limiting factors remain and weather conditions, together with crop genetic factors, become the primary limits to yield. Nonetheless, this interpretative approach has limitations for easily leached mobile nutrients (e.g. nitrate and sulphate) and in soils with very low cation exchange capacities that cannot retain sufficiently large

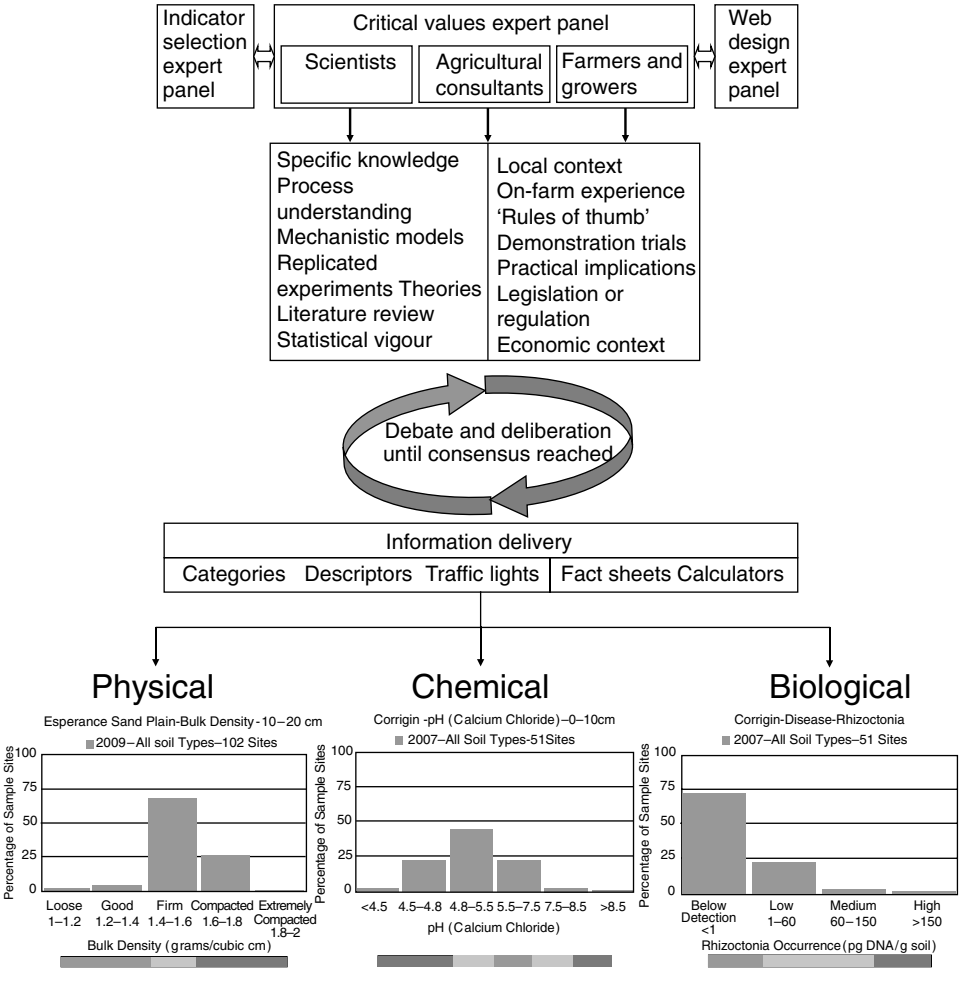


Figure 3.9 Example of the approaches used to develop a soil quality indicator package, highlighting the role of expert groups. These groups drew together a wide range of stakeholders with relevant information and experience including literature review and practical experience. Through facilitated discussion, the groups derived the relationships between yield response and a range of soil properties to inform the interpretation of the indicators used within the soil quality monitoring framework (www.soilquality.org.au) which focuses on soil quality for crop production. Data presentation using the derived categories, descriptors and traffic lights shown for three soil indicators as examples. For a colour version of this figure, please see Plate 3.4.

pools of cations such as K or magnesium (Mg). Interpretation also needs to take account of different crops; e.g., it is well known that cereals show yield limitation at a much lower level of soil test P than potatoes. Any sufficiency levels reported are inferred and not absolute and are consequently dependent both on the amount and quality of data available for analysis within key soil/crop/climate/management combinations and the approaches taken in data analysis (Figure 3.8). Changes in crop varieties and management practices may also mean that re-interpretation of sufficiency levels is required: e.g., a decline in the residual soil test P measured in row crops in Alabama was not accompanied by a decrease in yields; instead yields were found to have increased despite low soil P levels (Evans, 1987).

Wortmann *et al*. (2009) showed that the critical level of P for maize was affected by the previous crop with a critical level of 10 mg kg^{-1} (Bray extract) where maize followed soybean and 20 mg kg^{-1} where maize followed maize; they recommended that soil organic matter levels and pH be used together with soil test P values to improve soil fertility management decisions.

Base cation saturation ratios

Interpretation of soil tests on the basis of cation saturation is a common parallel approach to the use of sufficiency thresholds – especially in the USA. The basic cation exchange phenomena in soil which control the availability of calcium, magnesium and potassium and the impacts that the degree of saturation of one cation can have on the plant availability of itself and other cations are discussed in Chapter 6. Kopittke and Menzies (2007) highlight the historical development of the approach (often known as Albrecht analysis/interpretation), which resulted in the recommendation by Bear *et al*. (1945) that for an ideal soil 65% of the exchange complex should be occupied by Ca, 10% by Mg, 5% by K and 20% by hydrogen; it was considered that where this cation balance was achieved, chemical, physical and biological properties would all be in an appropriate equilibrium to support optimum plant growth. Review of the literature by Eckert (1987) and Kopittke and Menzies (2007) suggests that fairly wide variations in actual ratios are of little consequence for crop yield, quality or a wide range of soil physical and biological properties, as long as gross imbalances are not created. Consequently, sole focus in the interpretation of soil fertility on a target Ca/Mg ratio often leads to recommendations for management that are extremely expensive and have little impact on crop productivity or profitability.

Testing for mobile nutrients, e.g. nitrate

Measurement of soil mineral N (i.e. nitrate + ammonium, but often only nitrate because amounts of ammonium present are usually small) before planting or at a specific time during the crop growing season can be interpreted under certain conditions to give an indication of likely soil N supply. In climates without excessive overwinter leaching, the use of a pre-planting test for soil nitrate is widely used; in the western USA before 1982, 16 states were using such a test (Keeney, 1982). Values obtained for nitrate before planting were compared to the estimated crop N demand to obtain the likelihood of response to additional fertiliser. A pre-sidedress nitrate test has been developed for maize (Magdoff *et al*., 1984), which allows a period of nitrate accumulation under field conditions before sampling takes place, and therefore also reflects the mineralisation potential under field conditions. Similar approaches are used in many countries in Europe and these were summarised by Mengel (1991). Measurement of soil mineral N can be combined directly with analysis of N already in the crop (i.e. that already supplied by the soil) to predict seasonal soil nitrogen supply and thus guide fertiliser requirements (Defra, 2010). However, research has shown that this single 'snapshot' in time is often very unrepresentative of soil nitrogen supply (Knight *et al*., 2008; Murphy *et al*., 2009). The UK Fertiliser Manual (Defra, 2010) consequently recommends that sampling and analysis of soil mineral N is used to give guidance '… where the supply of plant available nitrogen in the soil could be unusually large, and particularly where organic manures have been used regularly in recent years', not as a precise prediction tool.

3.5 Managing soil fertility

Where yield is constrained by soil factors, perhaps diagnosed by plant or soil analysis, the next step is to determine what action might be taken by the land manager to adjust their rotation to optimise productivity/profit given the constraint and/or to implement management strategies that mitigate the constraint. Management strategies might seek to improve performance over the medium to long term (e.g. to increase effective rooting depth by improving drainage, removal of pans by cultivation and use of deep-rooted crops within the rotation) or seek an immediate impact (though to improve soil depth), 'shattering the underlying rock or hard layers with explosives [is] not in general use' (Russell, 1937). Local knowledge and farmer understanding of soil fertility, as indicated by crop performance, weed species and diversity and observable soil properties have been used to select sites which are most likely to respond to improved soil management practices (Suarez *et al*., 2001; Barrios and Trejo, 2003; Mairura *et al*., 2008). Farmers' understanding of their own soils is strongly orientated towards easily observed characteristics that affect production, such as texture (heavy or light land for cultivation), waterlogging and drainage after heavy rain, nutrient retention (hungry soils) and the structural condition of the soil (tilth, heart). Such variations are often the reasons why field boundaries occur where they do, and the fields may have indicative names, e.g. Sweetlea, Hungry field, Starvall. Integration of local knowledge with technical information can provide a foundation from which to determine key local constraints or to identify which potential management practices could be used at each site (Barrios *et al*., 2006). Careful targeting of proposed changes in soil management approaches to key crops and the selection of rotational systems to match geographic, market and social niches is needed to maximise effectiveness of any recommended interventions and to increase uptake by farmers (Ajayi *et al*., 2007).

3.5.1 Development of recommendations for targeted inputs

Most of the research supporting soil fertility management has focussed on fertiliser and lime recommendations, as both of these practices seek to provide an economic return to farmers over the timescale of a crop rotation, if not more quickly. 'If the soil test falls below the sufficiency level, how much fertiliser should be applied?' is the primary question, but there are a wide range of further questions needed to support management decisions to inform choices about the type, timing and placement of fertiliser in practice. Fertiliser type often affects the availability of the nutrients added; so, e.g., there is a wide range in concentration and availability of P from diammonium phosphate, triple superphosphate, farmyard manure and phosphate rock (Table 3.4). Soil factors, not least pH and moisture content at application, also affect the availability of nutrients from fertiliser additions.

Often the same or a similar series of yield response experiments are used to determine optimum fertiliser application rates post hoc, as described in Section 3.2.1 for the determination of suitability ranges (Figure 3.8). However, for the development of fertiliser recommendations, economic considerations are central, with the determination of the optimum fertiliser application from a response curve determined in part by the ratio between the price of a unit of fertiliser nutrient and the saleable value of the crop; hence, actual rather than relative yields are used. Where environmental impacts are also an important consideration, the risk of nutrient loss (e.g. by leaching or denitrification) may also be taken into account alongside economic considerations. A wide range of response models can be

Table 3.4 Typical composition of some common fertilising materials; all organic fertilisers are very variable and consequently these data provide only an indication of likely composition.

	%			
	N	**P**	**K**	**Other notes**
Ammonium sulphate	21			24% S
Ammonium nitrate	32–34.5			
Urea	46			
Diammonium phosphate	21	23 (soluble)		
Triple superphosphate		20 (soluble)		14% Ca
Rock phosphate		12–16 (slowly soluble)		31–35% Ca
Potassium chloride			50	
Potassium sulphate			42	17% S
Cattle farmyard manure	0.6; 10% readily available	0.08 (soluble)	0.6 (soluble)	25% DM 0.1% S
Pig slurry	0.4%, 70% readily available	0.04 (soluble)	0.2 (soluble)	4% DM, 0.04% S
Poultry (broiler) litter	3%, 33% readily available	0.65 (soluble)	1.3 (soluble)	60% DM, 0.3% S
Greenwaste compost	0.75%, 3% readily available	0.06 (soluble)	0.4 (soluble)	60% DM, 0.05% S

Source: Data adapted from Defra (2010).

used but each is likely to provide a different estimate of the optimum fertiliser rates, and it is most important that a model is chosen so that it is appropriate to the data available. A good response model should (Cooke, 1982):

1. define both the slope of the rising part of the curve and the slope beyond the peak;
2. define accurately the yield near the optimum dressing and the dressing itself.

Actual yields and profitability are likely to have been affected by a wide range of factors other than those varied in the experiment, especially if the data are collated from a series of experiments carried out at different sites and in different years. Consequently, response curves are only valid as the basis of advice to farmers under the same conditions as used in the experiments. Although it is possible to compile tables of average responses of crops to fertilisers at various soil sufficiency levels, it is not clear that these provide anything other than very general guidelines to farmers.

For less mobile nutrients (e.g. P and K), fertiliser recommendation systems now commonly use the soil sufficiency level/range as a target value and develop a fertiliser policy which seeks to achieve/maintain this value (on a rotational basis), i.e. fertilising the soil. This approach often recommends applications of small amounts (maintenance dressings) of fertiliser, even where soil test values are above the sufficiency level, to replace the amounts likely to be removed by the crop to be grown. Olson *et al*. (1982) reported on a long-term comparison study of fertiliser recommendations based purely on the sufficiency approach (applications only where fertiliser response was likely) and those made by a number of commercial laboratories using a build/maintenance approach. No significant difference in crop yields were recorded, but fertiliser costs where a

maintenance approach was used were on average twice those where fertiliser was applied on a sufficiency basis. Recommendations in the UK state that 'Once deficiency has occurred, a fresh application of P and K is most unlikely to be available for uptake by roots in time to benefit the crop being grown' (Defra, 2010). In addition, even in the low range below the soil sufficiency index, it has been observed that up to 40% of fields may not respond profitably to fertiliser application (Havlin *et al*., 1999), in part due to nutrient supply from pools not accounted for in the soil test, or available nutrients below the sampling depth (Davis *et al*., 1996), as well as the impact of other limiting factors in the year of observation. In farming systems with relatively stable crop rotations and production systems, it should be possible to couple plant and soil analysis for P and K to provide indicators of the effectiveness of management practices, rather than using such data to derive fertiliser recommendation *per se*. This type of farm-specific monitoring should allow modification of management underpinned by an understanding of the principles governing P and K availability (Chapters 5 and 6) rather than the application of average recommendations.

For mobile nutrients, such as N, fertiliser recommendations are usually based on yield potential; these are most often expressed as a farm/field-specific yield goal. This yield goal is used to determine the likely crop N demand in the season. A range of information can be used to guide the farmer's yield goal, including previous yields achieved at the site. The requirement to predict the likely weather, disease risk and other factors potentially impacting on crop growth is explicitly placed with the farmer or their advisor. In dryland agriculture, it is usually considered advantageous to set the grain yield goal above that of average yields to fully take advantage of the potential for above-average growing conditions, e.g. above-average rainfall (Johnson, 1991). However, Hergert (1987) highlighted the need to improve yield goal determination for fertiliser recommendations as 50% of farmers attained yields equivalent to only 80% of their yield goal. For N fertiliser, if the yield goal is too high, fertiliser recommendations will overestimate requirements, farmers will waste money and there is an increased risk of N loss to the environment. Development of new technological approaches that can be used during the season in the field (e.g. canopy reflectance, Raun *et al*., 2001) may mean that it becomes increasingly possible to predict grain yield in-season and consequently adjust the fertiliser recommendations based on projected N demand.

Fertiliser N requirements are calculated from the crop requirement by adjusting for estimates of the soil N supply corrected for in-season losses:

$$\left(\text{Amount of N Fertiliser Needed}\right) = \left(\text{Crop N Requirement}\right) - \left(\text{Soil N Supply}\right) + \left(\text{N Losses}\right)$$

and then adjusting for any nutrients to be supplied from manures, biosolids, etc. Improved fertiliser recommendations therefore depend in part on the ability to estimate N mineralisation and N losses (Mulvaney *et al*., 2001; Zebarth *et al*., 2009), and also amounts and rates of nutrients supplied from manures and other organic materials, e.g. animal manures, urban green waste composts, etc. Cooke (1982) outlined how the range of factors affecting crop response to nitrogen fertiliser had been integrated into an N index system. This used information on previous cropping and manuring to predict the likely response of sites to nitrogen fertiliser, i.e. providing an adjustment for soil N supply based on data collated from many years of field experiments (e.g. MAFF, 1996).

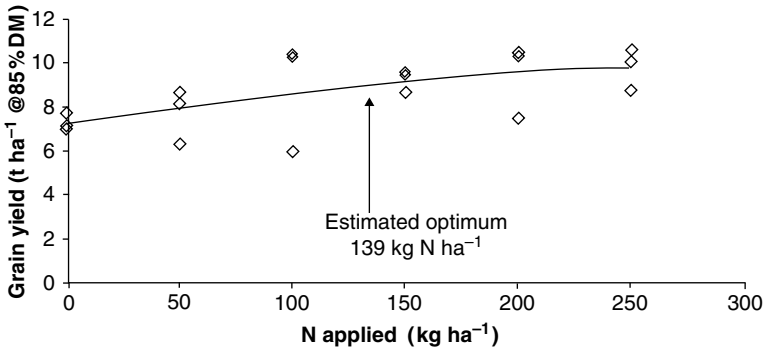
The development of models of soil nutrient dynamics (Shaffer *et al*., 2001) may allow these to be integrated into decision support systems for fertiliser recommendations. This may be: (1) on a static basis, so that the model is run once to provide information on predicted

soil N supply or losses, or (2) dynamically in which the model is run weekly or monthly throughout the growing season and the later applications of fertiliser are adjusted for model-predicted crop requirements, soil N supply and losses. Using such a system, fertiliser recommendations may be able to be revised to allow for the differences from average weather conditions or crop growth. However, even with such dynamic systems, it is not realistic to expect that fertiliser recommendations for the current crop will ever exactly match the optima measured at harvest due to the influence of the (largely) unpredictable weather on crop growth and soil processes. The use of models also provides the opportunity to predict the nitrogen response curve for a site; this information can be used to determine how sensitive crop yield is to small changes in rates or timings of fertiliser application. See an example in Figure 3.10.

3.5.2 Developing recommendations for integrated soil fertility management

There is an increasing use of broader integrated approaches to the assessment of soil fertility which consider the impact on plant growth of the emergent properties and processes arising from ecosystem-level interactions of plants/roots with physical, chemical and biological factors in the soil. It is therefore clear that soil fertility management cannot be restricted to advice on the seasonal management of nutrient, water inputs or even the use of green manures. Soil and water conservation measures, crop breeding and rotation design, tillage, drainage and pest management strategies together with farm landscape design (presence, composition and location of shelter belts, buffer strips, hedges) may all form important components in the integrated management of the below-ground ecosystem (Figure 3.11). In the same way that soil fertility is one aspect of a more integrated definition of soil quality (Section 3.2.3), integrated soil fertility management can be considered as one aspect of broader strategies for integrated natural resource management (Vanlauwe *et al*., 2006).

Production practices such as the integration of reduced tillage, retention of crop residues, targeted planting and farm input use and the use of legumes in rotation (conservation farming approaches), legume agroforestry (fertiliser tree) systems, the integration of green manure and dual purpose legumes and the careful use of animal manures (Sanchez and Salinas, 1981; Palm *et al*., 2001) are common where more integrated approaches to soil management are used. All combine inputs of organic matter with other changes to management systems. Because of the role of decomposition in providing energy to the soil ecosystem, regular inputs of organic matter can change the biomass, activity and diversity of soil organisms driving changes to a wide range of soil physical and chemical properties. Hence, responses to additions of organic materials to cropping systems are complex and interactive and rarely can be explained by a simple causal chain. In addition, there is increasing interest in the use of soil inoculants or plant sprays developed as plant growth stimulants or biopesticides (see Section 3.3.2). Rupela *et al*. (2006) reported findings of an experiment (established in 1999), which investigated the role of plant biomass (rice straw or farm waste combined with hedge clippings) as an input, together with applications of rock phosphate, biopesticides and reduced tillage in a rainfed cropping system on a Vertisol in the semi-arid topics (India). After a first year in which low-cost input/biologically based systems had lower yields (attributed to the lag phase in release of N and P from complex organic inputs), crop yields were close to those in optimally managed conventional plots, and net income to farmers was significantly higher due to the lower cost of inputs. N and P balances were positive and consequently there was no nutrient depletion; soil organic matter, microbial biomass C and



Method	Optimum*	RB209	SUNDIAL	
			Defaulf weather and yield	Actual weather and yield
Recommendation	139	182	162	141
Calculated yield*	9.1	9.5	9.3	9.1
%difference from optimum yield		4	2	0

**Calculated from linear plus exponential curve fitted to trial data.*

Figure 3.10 Evaluation of a dynamic model (SUNDIAL) for fertiliser recommendation (Smith *et al.* 1996). In 1997, a project was initiated to establish a series of N response trials on working farms across the UK and to evaluate the performance of model recommendations across a range of typical crops and soils. Data are presented from one of these sites as an example. The site was a sandy clay loam soil in Suffolk, Eastern England. Winter oilseed rape (cv. Navajo) was harvested on 25 July 1998 and yielded 4.3 t ha^{-1} (@ 90% DM). Crop residues were chopped and incorporated and 40 t ha^{-1} of farmyard manure taken from the piggery was applied just before ploughing. Winter wheat (cv. Equinox) was drilled on 3 October 1998. The farmer was expecting a yield of 11–12 t ha^{-1}. The N response curve obtained in the field (three replicate plots of 6 N rates) was fairly flat and the replicate plots quite variable due to the N supplied by the pig manure. The response curve was fitted by a linear plus exponential relationship (Genstat) with an optimum estimated at 139 with a standard error of 17 kg N ha^{-1}. The actual yield obtained in the field was much lower than the farmer's target only reaching about 9.5 t ha^{-1}. The standard UK reference book *Fertiliser Recommendations for Agricultural and Horticultural Crops* (RB209; MAFF, 1996) recommended an application of 182 kg N ha^{-1}, while predictive use of the SUNDIAL model recommended 162 kg N ha^{-1}. The SUNDIAL recommendation was not significantly different from the measured optimum, while the RB209 recommendation was a significant overestimate. However, this over-application of N had little effect on the yield achieved, but may have increased the residual mineral N available for leaching after harvest. In plots that had received 250 kg N ha^{-1}, mineral N was increased very significantly above those plots which had received N applications close to the optimum. When SUNDIAL was used retrospectively, i.e. with the actual weather and the target yield set at the actual optimum achieved, the SUNDIAL recommendation almost exactly predicted the measured optimum. It is important that SUNDIAL achieves good retrospective predictions as this demonstrates that the model can be used reliably to carry over information from one year to the next without introducing significant errors.

N levels were increased in the treatments receiving additional C inputs. Such integrated system experiments are of considerable value in demonstrating how the principles underpinning integrated soil fertility management can be implemented in practice within inherent site constraints. Best practice may well be region and even site specific, e.g. the local availability of the biomass and biopesticides in the earlier example. However, such system management experiments are often the despair of scientists seeking to understand the

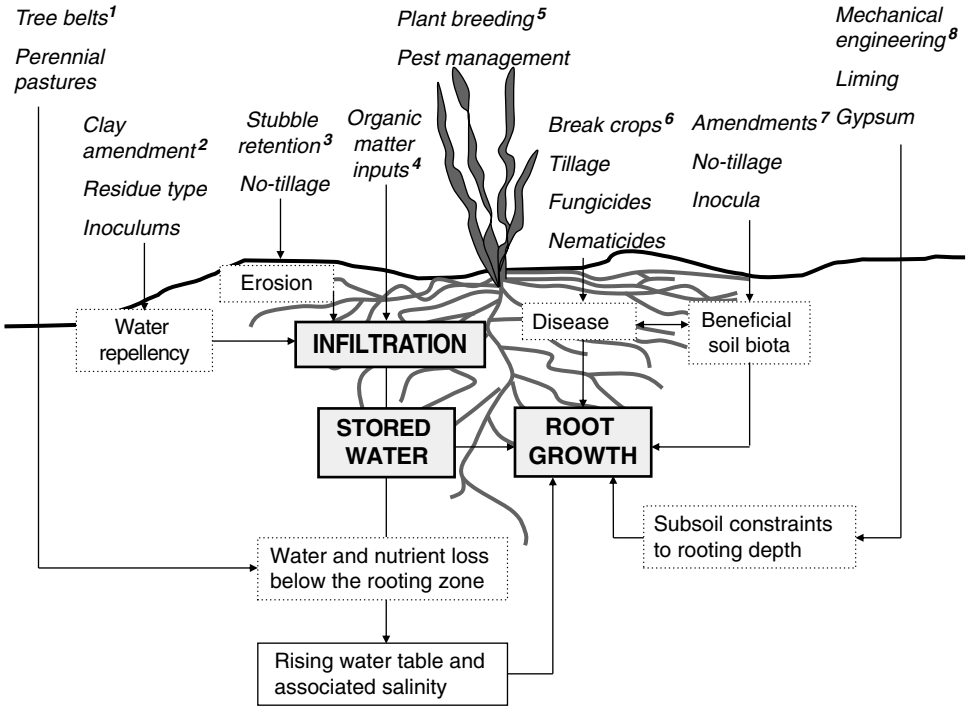


Figure 3.11 Developing integrated strategies for effective capture and utilisation of rainfall together with management of soil water is critical to achieve crop growth in dryland cropping systems (Tow *et al.*, 2012). In South Australia, a range of soil management approaches are integrated within farming systems so that the potential yields (defined by available water in any season) can be attained. These include (1) introduction of tree belts (Robinson *et al.*, 2006) and deep rooting perennial pastures to slow a rising (often saline) water table. (2) While wax degrading micro-organisms have been isolated (Roper, 2004), their success as inocula under field conditions has been limited. Instead clay amendment is an economically viable option (Hall *et al.*, 2010) to overcome water repellence where it can be sourced locally (e.g. from subsoil on the same farm). (3) No-tillage and stubble retention practices are now commonplace to manage erosion and ensure maintenance of soil carbon levels and associated soil biological function (Hoyle and Murphy, 2006). (4) Organic matter stabilises soil aggregates and improves water infiltration into soil by contributing to the development of a more porous soil structure (Hoyle *et al.*, 2012). (5) Plant breeding for improved water use efficiency (more grain per mm plant available water) and tolerance to toxicity (e.g. Al; Tang *et al.*, 2003a). Early vigour lines (Ludwig and Asseng, 2010), which enable roots to track early season water and nutrients in leaching soils, also have the benefit of growing the root tip through surface soil constraints (e.g. diseases) quicker. (6) Development of disease-suppressive soils has occurred through crop management and rotation (Wiseman *et al.*, 1996). (7) Amendments to soil can have either positive or negative effects on the soil biota (Bunemann *et al.*, 2006) which can impact on the level of micro-organisms involved in carbon and nutrient cycling. (8) Deep ripping to remove compaction and at same time including gypsum or lime (Tang *et al.*, 2003b) to depth to ameliorate subsoil constraints. Use of controlled traffic (Kingwell and Fuchsbichler, 2011) to stop vehicle movement over the majority of the soil surface and tractors with tank tracks instead of wheels to minimise compaction. For a colour version of this figure, please see Plate 3.5.

ecological interactions underpinning soil fertility and their links to individual component management practices. In general, in such systems, scientists have been very effective in cataloguing the impact of management practice changes on the root/soil system (chemical, physical and biological properties, e.g. Mäder *et al.* (2002) and Cookson *et al.* (2008)) but much less effective in developing management systems that achieve targeted changes.

3.5.3 Challenges for soil fertility management in the twenty-first century

As already noted, climate change coupled with increased costs and declines in the availability of many of the common inputs will necessitate changes to soil fertility management in the twenty-first century. Reduced tillage, legumes and other N-fixing plants as intercrops, green manures or as hedgerow trees and the selection of crops and varieties to promote rhizosphere-mediated nutrient availability have already been integrated into so-called 'sustainable' agricultural systems. It is likely that these and similar approaches will become a more common part of conventional agricultural systems as the twenty-first century progresses. These changes will require soil scientists and agronomists in the developed world to learn from their counterparts working in developing countries where farmer participatory research has been successful in promoting improved soil fertility, crop yield and farmer livelihoods. The challenge for all agricultural systems is to achieve sustainable intensification; this will require increased focus on the use of biological processes and potentials within the soil-plant system.

Simple single-factor response experiments (or even multifactorials), as commonly used for fertiliser trials, have little relevance in the evaluation of integrated soil fertility management approaches. Each input (e.g. compost, inoculant or new crop variety) or management practice (e.g. change in depth of tillage, incorporation of crop residues or green manures) has interacting impacts on multiple organisms and on the soil physical and chemical properties defining their habitats. Consequently, though there is a myriad of data cataloguing the impact of many of these practices on soil physical, chemical and biological practices, there is little systematic evaluation of these integrated management systems on the maintenance of soil fertility, as broadly defined, except on a case-by-case basis. Understanding how soil-plant systems respond to management and climate will require a more ecologically based approach to experimental design and analysis. Furthermore, experiments will need to be maintained for sufficient years to enable the resistance and resilience of systems to be determined and the underpinning soil–plant interactions to establish.

Integrated soil fertility management approaches often have at their heart the incorporation of organic inputs to the soil-plant system. However, if these systems are to become more widely adopted, consideration is needed of how the organic matter inputs required can be sustained over decades. The plant is the conduit bringing energy into the soil ecosystem; hence in natural ecosystems, net primary production is often strongly linked to the biomass and activity of the soil organisms. In many environments, effective capture of solar radiation is limited by water availability; in 'conventional' agricultural systems, plant breeding has focussed on increasing the biomass of the marketable component (e.g. grain, fruit) at the expense of crop residues, hence limiting or reducing inputs. A combination of rotational planning (exploiting the benefits of plant diversity in space and time) and plant breeding approaches (both to manipulate rhizosphere inputs, to increase amounts or manipulate quality of residues) will be needed to overcome this potential constraint for integrated fertility management approaches in the future.

The specialisation of soil science researchers has often led to their dissociation with the practical implementation of soil fertility; one might see the application of molecular methods to the analysis of soil microbial function as a particular example of this; function must be linked to process. The soil-plant ecosystem functions as a result of the complex interactions between soil organisms and their habitats, so the effective development of soil fertility

management in the twenty-first century should be underpinned by collaborative interdisciplinary investigations emerging from dialogue amongst researchers, extension specialists and farmers/growers. Integrated soil fertility management should be at the heart of a global approach to improving the sustainability of agriculture, its impact on food security and the environmental impact of the industry. This will require the development of new plant genotypes, management systems, indicators and recommendations.

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